

The Fast Loss Electron Proton Instability

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1 Introduction

Very fast, high frequency, transverse instabilities have been observed in the Los Alamos PSR[1, 2, 3] and the AGS Booster[4].

- instability can “hold off” for 100 μs
- e-folding time ~ 10 turns.
- 50% beam loss in $\sim 20 \mu\text{s}$.
- if due to Z_\perp then $Re(Z_\perp) \sim 10\text{M}\Omega/\text{m}$, and broadband
- ω_c strong function of tune/threshold current.
- $\omega_c = \omega_c(t)$ during instability

Could these be due to trapped electrons?[1, 2, 3, 4, 5, 6, 7, 8, 9, 10].
PSR and AGS Booster are unique with the instability causing large losses in a short time.

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2 Data from the AGS Booster

AGS Booster parameters during study

| parameter | value |
|------------------------|----------------------------|
| circumference | $2\pi R = 202\text{m}$ |
| kinetic energy | 200MeV |
| rms frequency spread | $\approx 300\text{Hz}$ |
| nominal betatron tunes | $Q_x = 4.8, Q_y = 4.95$ |
| beam pipe radius | $b = 5\text{cm}$ |
| injected beam radius | $\approx 3\text{cm}$ |
| nominal chromaticity | $Q'_x = -3, Q'_y = -1$ |
| sextupoles off | $Q'_x = -7.5, Q'_y = -2.6$ |
| rf voltage | 0V |
| linac RF frequency | 200MHz |
| injected pulse length | 200 to $450\mu\text{s}$ |
| revolution period | 1207ns |

Diagnostics:

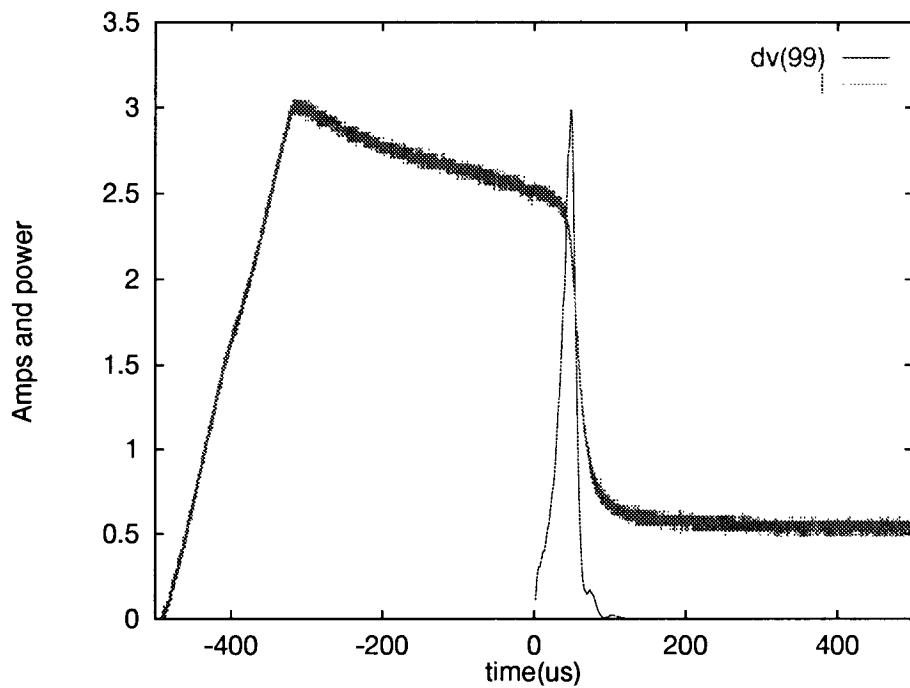
- current transformer, $0 \rightarrow 100$ kHz
- wall current monitor $1 \rightarrow 200$ MHz
- horizontal and vertical split can capacitive BPMs $1 \rightarrow 200$ MHz

BPMs were sampled at 1GHz. Sum and difference good to $\tau = 1$ ns.
 Checked FFTs, Mountain ranges, narrow band power P_n .

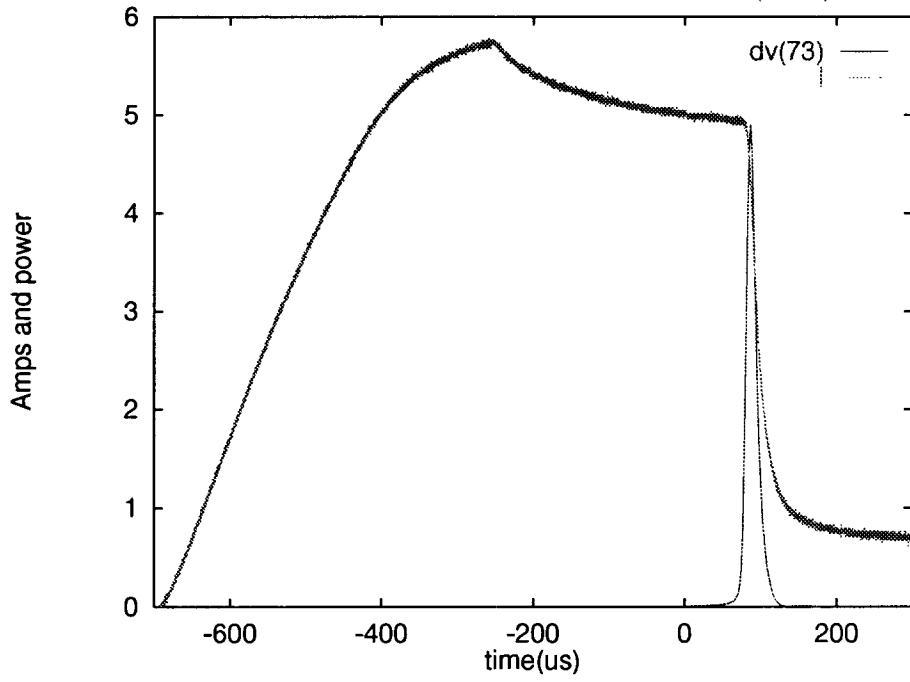
$$F_{n+1} = (\cos(\tilde{\omega}\tau)F_n - \sin(\tilde{\omega}\tau)G_n)e^{-\alpha\tau} + S_n \quad (1)$$

$$G_{n+1} = (\sin(\tilde{\omega}\tau)F_n + \cos(\tilde{\omega}\tau)G_n)e^{-\alpha\tau} \quad (2)$$

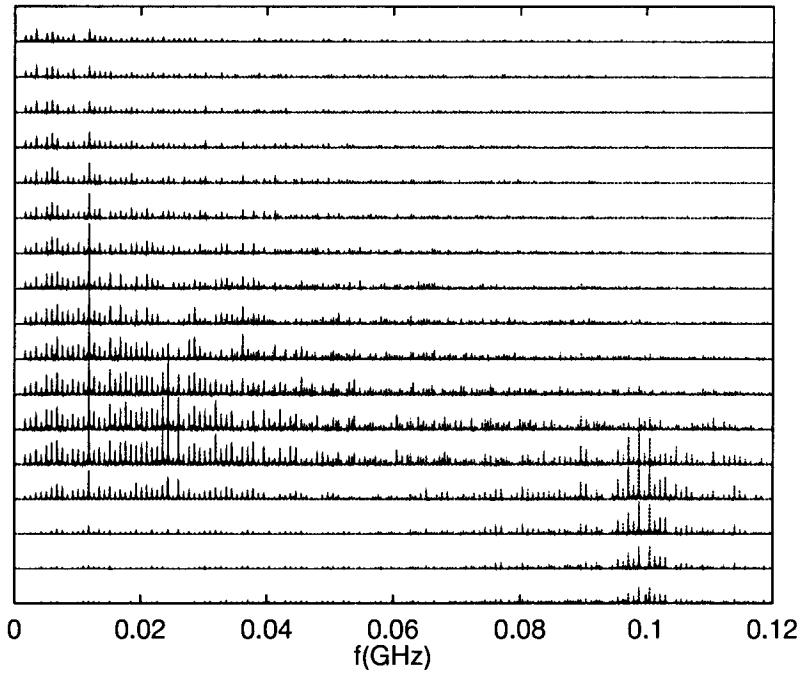
$$P_{n+1} = e^{-\tau/\tau_0}P_n + G_n^2 \quad (3)$$



$Q_x = 4.75, Q_y = 4.50$, sextupoles off
 power in narrow band vertical difference (red), and beam current (green).



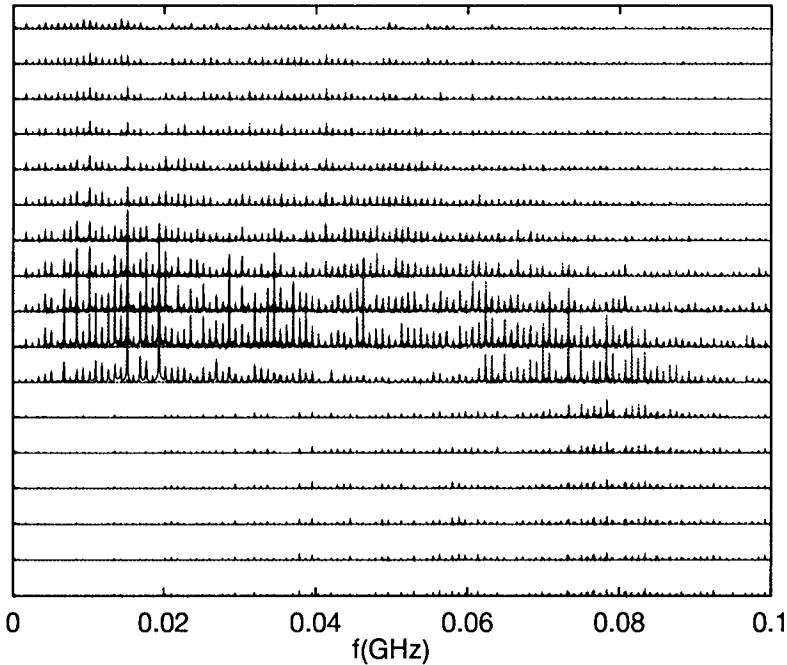
$Q_x = 4.80, Q_y = 4.95$, sextupoles off
 power in narrow band vertical difference (red), and beam current (green).



Spectral amplitude of vertical sum (blue) and difference (red).

$Q_x = 4.75$, $Q_y = 4.5$, sextupoles off

FFTs used ten turns of data (12 μ s between traces).

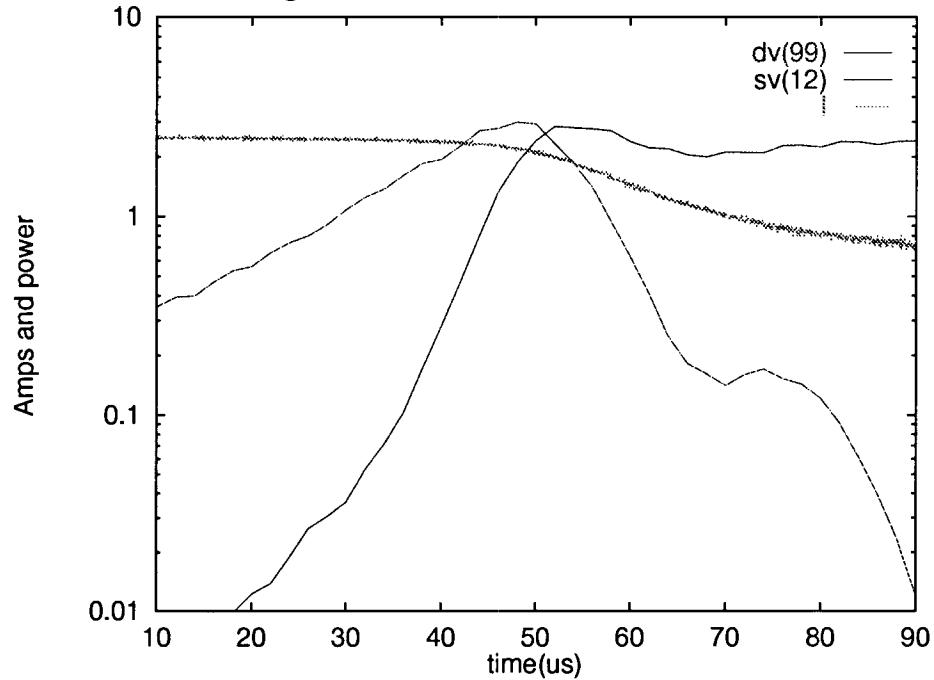


Spectral amplitude of vertical sum (blue) and difference (red).

$Q_x = 4.8$, $Q_y = 4.95$, sextupoles off

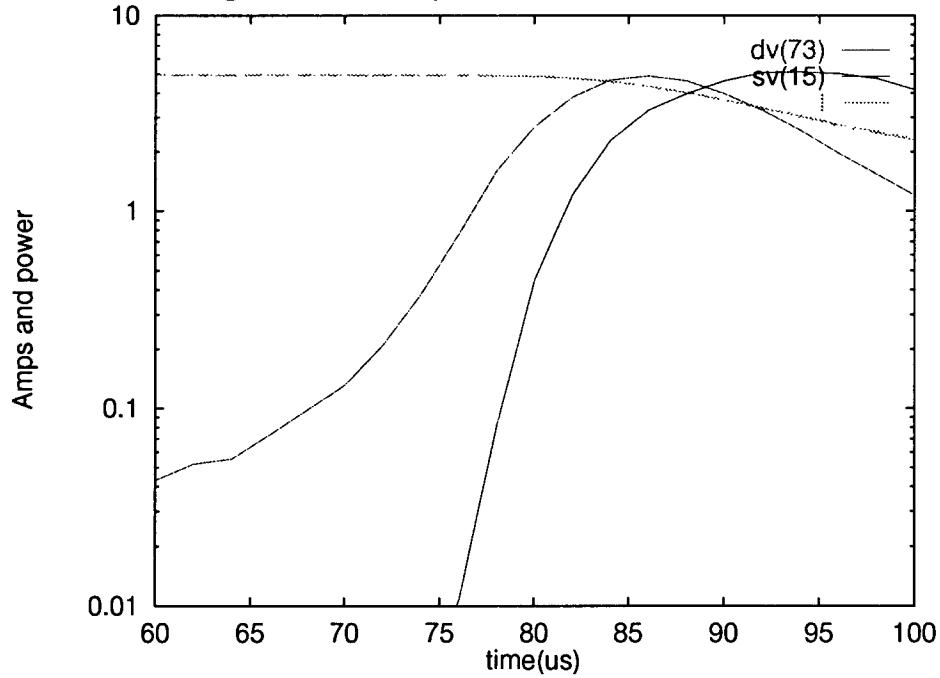
FFTs used ten turns of data (12 μ s between traces).

Narrow band signals



$Q_x = 4.75, Q_y = 4.5$, sextupoles off

Net smearing time $\approx 2 \mu\text{s}$.



$Q_x = 4.8, Q_y = 4.95$, sextupoles off

Net smearing time $\approx 2 \mu\text{s}$.

First case $dv \approx A \exp(t/\tau_I)$ with $\tau_I = 5.7\mu\text{s}$.

Transverse growth rate of a cold coasting beam,

$$Im(\Omega) = \frac{qcI_{peak}Re(Z_\perp)}{4\pi E_0 Q_\beta}, \quad (4)$$

e-folding time of $2 \times 5.7 = 11.4\mu\text{s}$ implies $Re(Z_\perp) = 5.4\text{M}\Omega/\text{m}$.

Many unstable lines implies broad band.

Coherent transverse space charge impedance is

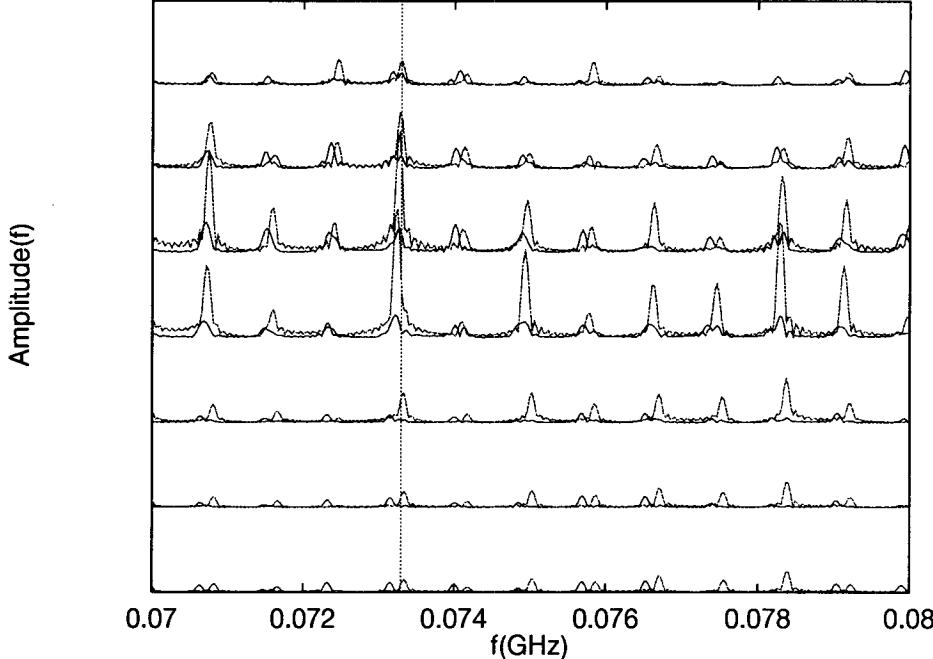
$$-i \frac{RZ_0}{\beta^2 \gamma^2 b^2} = -i 8.4\text{M}\Omega/\text{m}.$$

With $\beta\gamma = 0.69$.

In second case $d \log P/dt$, peaks at 350/ms.

If Z_\perp then $Re(Z_\perp) = 8.8\text{M}\Omega/\text{m}$.

High resolution of second case



The vertical line is at 73.3MHz. The nearest vertical peak shifts down by 90 kHz = $0.11f_{rev}$ during the instability.

Bare tunes set at $Q_x = 4.80$, $Q_y = 4.95$, sextupoles off. ($\Delta Q_y \approx 0.1$)
 Smaller vertical tune did not increase the threshold ($\beta(s)$ dependence).
 I_{peak} similar during normal operations with $\omega_s \lesssim 100/\text{ms}$, but no instabilities.

3 Coasting Beam e-p Model

The coasting beam theory in the linear limit with no electron multipactor has been carefully explored[5, 6, 7, 8].

Linearize transverse forces and neglect frequency spread.

Neglect quadrupole images from non-round beam pipe.

The average force on a proton is given by

$$\bar{F}_p(\theta, t) = \frac{e\lambda_p}{2\pi a^2 \epsilon_0} \left(\frac{a^2}{b^2} \frac{\bar{y}_p(\theta, t)}{\gamma^2} - f[\bar{y}_p(\theta, t) - \bar{y}_e(\theta, t)] - f \frac{a^2}{b^2} \bar{y}_e(\theta, t) \right).$$

The average force on an electron is

$$\bar{F}_e(\theta, t) = -\frac{e\lambda_p}{2\pi a^2 \epsilon_0} \left(\frac{a^2}{b^2} \bar{y}_p(\theta, t) - [\bar{y}_p(\theta, t) - \bar{y}_e(\theta, t)] - f \frac{a^2}{b^2} \bar{y}_e(\theta, t) \right).$$

Setting $\bar{y} = Y(\theta, t)$ and applying the force laws give:

$$\ddot{Y}_p = \left(\frac{\partial}{\partial t} + \omega_0 \frac{\partial}{\partial \theta} \right)^2 Y_p = -\omega_\beta^2 Y_p + \bar{F}_p(\theta, t)/\gamma m_p \quad (5)$$

$$\ddot{Y}_e = \left(\frac{\partial}{\partial t} \right)^2 Y_e = \bar{F}_e(\theta, t)/m_e. \quad (6)$$